INFRASOUND DETECTION OF ROCKET LAUNCHES

Keith L. McLaughlin, Anna Gault, David J. Brown
SAIC, Center for Monitoring Research

Sponsored by US Army Space and Missile Defense Command
Contract No. DASG60-96-C-0064

ABSTRACT

The satellite launch industry is a multi billion-dollar international industry with over 100 commercial and military satellite launches conducted in 1999 alone. Rocket launches from both Cape Canaveral Air Force Station (CCAFS) and Vandenburg Air Force Base (VAFB) have been observed at operational infrasound stations monitored by the Prototype International Data Center (PIDC). As more IMS infrasound stations are installed worldwide, we can expect to more frequently observe rocket launches. Rocket launches may serve as useful "ground truth" data and/or Confidence Building Measures (CBM) to test and demonstrate IMS infrasound capabilities. Commercial and military launch facilities include Baykonyr in Kazakhstan, Plesetsk in Russia, Jinyu, Wuzhsi, Jiuquan, Xichang, and Taiyuan in China, Kourou in French Guinea, Alcantara in Brazil, Tanegashima in Japan, Vandenburg AFB and Cape Canaveral AFS in US, and the new Boeing ocean-going launch platform in the Pacific Ocean.

"Summer season" Space Shuttle launches are seen at the experimental DLIAR (2550 km) infrasound array in New Mexico and the more recently installed infrasound array, ISM (2780 km), in Canada. These long-range observations are strongly correlated with the geometry of stratospheric winds across North America. The 1-4 Hz signals arrive within 5 degrees of the nominal azimuth.

In order to take advantage of favorable West-to-East propagation, waveforms were examined for 14 VAFB launches in 1999 at SGAR (680 km) and DLIAR (1300 km). Detections were seen for a Titan IVB launched 5/22/99 and a Delta II launched 04/15/99. Interestingly, the Delta II of 02/22/99 and the Atlas IIA of 12/18/99 were not detected although these two rockets are of similar size. Upper atmospheric wind conditions should have been favorable for several of the detections, however noise levels were often high at SGAR and DLIAR. Relative amplitudes of the signals are consistent with relative thrusts (700 vs. 1700 thousand lbs). Observed arrival azimuths were within 5 degrees of nominal. Detailed analysis of DLIAR signals indicate azimuth can be tracked down-range from the launch site for two minutes. Arrival times and phase velocities are consistent with stratospheric propagation and nominal infrasound travel times to SGAR (2340 s) and DLIAR (4440 s). The signals were best observed between 0.1-2 Hz.

Long-range detections of Space Shuttle, Titan IVB, and Delta II launches are very encouraging. The Space Shuttle burns about 1 KT of liquid oxygen and hydrogen per minute. Therefore the equivalent explosive yield of the extended infrasound source is between one and two orders of magnitude smaller than 1 KT. The Titan IVB and Delta II launch vehicles are an order of magnitude smaller than the Space Shuttle.

OBJECTIVE

This work examines rocket launches as potential ground truth events to demonstrate long-range IMS infrasound capabilities such as detection and azimuth estimation as a function of changing atmospheric conditions.

REVIEW

Man-made low-frequency infrasound (less than ~20 Hz) may be excited by large strip-mine blasts, atmospheric explosions, gas pipeline ruptures, rocket launches, orbital (and sub-orbital) vehicle reentry sonic booms, and aircraft sonic booms. Some sources are point like (explosions) and others are distributed along a trajectory (meteors, sonic booms and rocket launches). The literature contains several examples of infrasound from missile launches in the late 1960's and early 1970's. Most results were an off-shoot of infrasonic research done for long-range atmospheric nuclear test detection. Interest in the topic diminshed as nuclear powers shifted to underground testing. Publications by Fehr (1967), Donn et al (1968), Kaschak (1969), Kaschak et al. (1970), Donn et al. (1971), Cotton and Donn (1971), Balachandran et al. (1971a), Balachandran et al. (1971b), and Posmentier (1971) provided an analysis of the frequent and large rocket launches of the early manned space program.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**

4. TITLE AND SUBTITLE **Infrasound Detection Of Rocket Launches**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **SAIC Center for Monitoring Research,1300 N. 17th St. Suite 1450,Arlington,VA,22209**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Proceedings of the 22nd Annual DoD/DOE Seismic Research Symposium: Planning for Verification of and Compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT) held in New Orleans, Louisiana on September 13-15, 2000, U.S. Government or Federal Rights.

14. ABSTRACT
See Report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

- Intensity was found to depend on thrust, trajectory, and sound speed and wind along the path. Rockets as small as 50 Klbs thrust and as large as 7,500 Klbs thrust (Saturn-V) were observed at long-range (900-1500 km). Amplitudes for the largest Saturn-V rockets ranged from 1 to 20 microbar near 1 Hz.
- Strong seasonal effects on detection were observed. For paths from Cape Canaveral Air Force Station, Florida, to stations in New Jersey and New York over a 12-month period (298 launches) the monthly detection percentages ranged from 10 to 80%. It was found that long-range rocket infrasound propagates primarily in the stratospheric waveguide (below 50km) and the existence of this waveguide depends strongly on the presence/absence, geometry, and direction of the jet streams at about 50 km altitude. Temperature and wind soundings coupled to 2D and 3D ray tracing was found to adequately explain the observed seasonal behavior.
- In situations where rockets were launched "toward" the receiver, first arriving waves were often "apparently supersonic" generated by the re-entry phase of the 1st stage booster entering the atmosphere closer to the station than the initial launch site. Waves with "apparently sonic" velocities were observed to arrive at azimuths from the launch site and the ascent trajectory.
- Dominant frequencies were generally between 0.1 and 1 Hz (although the infrasound systems of the time severely attenuated frequencies above 1 Hz). Dominant frequencies appeared to be related to solid vs. liquid fuel with solid rocket missiles having high somewhat frequencies, 0.1-2 Hz. It was noted that solid fuel missiles have higher accelerations and reach Mach 1 sooner.
- It was argued the infrasound source mechanism was aerodynamic (sonic booms) rather than rocket exhaust and that the largest signals were excited at altitudes near the tropopause and velocities above Mach 1. A) The frequency content of the supersonic re-entry phase was similar to the ascent phase. B) Recordings in the vicinity of a launch or static firings (Fehr 1967) were broadband (above 4 Hz to audible) with peak values in the 8-16 Hz frequency bandwidth and differed from lower frequency long-range infrasound. C) Saturn rocket engine static firings at ground level in both Florida and Huntsville, Alabama, were never observed in New Jersey or New York despite often-favorable propagation conditions and orientations of the static firings.
- Long-range infrasound arrived within 5-8 degrees of expected azimuths (when corrected for launch path) consistent with cross wind effects predicted by 3D ray tracing.
- Near-range infrasound observations of static firings of individual Saturn-V "F1" engines (1,500 Klbs thrust) are consistent with an equivalent far-field source of 75,000 microbars at 1m peaked near 8 Hz during continuous runs (171 DB). During startup and shutdown, the source was more broadband and showed peaks at 4 and 16 Hz.

Long-Range Attenuation Models and Equivalent Explosive Yield

Stevens et al. (1999) recently conducted a review of long range explosion generated infrasound propagation. They found the Whitaker (1995) relationship generally the most robust for low yields.

$$\mathrm{Log}(P) = 3.37 + 0.68\,\mathrm{Log}(W) - 1.36\,\mathrm{Log}(R) + 0.019\,v,$$

where P is pressure in Pa (1 Pa = 10 microbar), W is yield in kiloton, R is range in km, R is range in degrees, v stratospheric wind velocity in m/sec. The relation has a strong dependence on atmospheric winds where v is positive if the wind is in the direction of propagation and negative if the wind is in the opposite direction of propagation. Upper atmospheric winds often attain velocities of over 50 m/s causing variations in amplitude of a factor of 20 or more. The attenuation relationships are all for surface source and receiver and are not generally considered valid for short-range propagation (< 200 km). If we apply the Whitaker attenuation relation to the Saturn-V historical literature data (0.1-2 Pa at 1500km, 0.1-1 Hz) we can estimate equivalent yield ranges of 0.07-6 tons (no wind), 1.7-150 tons (50 m/s head winds), 0.003-0.25 tons (50 m/s tail winds). These "equivalent" yield levels in the 1 Hz band are consistent with the rate of energy expended by the Saturn-V.

The total propellant (oxidizer plus fuel) available in a Saturn-V first stage (7,600 Klbs thrust) was about 2.3 Kt burned over a period of about 150 seconds or roughly equivalent to a 15-ton explosion every second for 150 seconds. The rate of energy release for the Space Shuttle (maximum thrust of 7,700 Klbs) is similar. The shuttle's three main engines (375 Klbs. thrust each) and 2 solid rocket boosters (SRB's) (3,300 Klbs thrust) burn between 1-1.3 Kt of propellant in 120 seconds to attain an altitude of about 50 km. The main engines then consume a maximum of 600 tons of propellant for another 5-6 minutes. If we assume the chemical efficiency of rocket fuel is close to

TNT, this is equivalent to a 10-ton chemical explosion every second. This is analogous to the ripple-fire problem in seismology where a strip mine may fire a series of smaller explosions spread out over time. For comparison, the first stage of a theater ballistic missile (TBM) (34-50 Klbs thrust) burns ~3 tons of fuel in ~90 seconds which is about 1/400th the amount of the shuttle in 80% of the total time. The actual infrasound excitation mechanism is uncertain. While the far-field mechanism may be supersonic shock waves, the expanding transonic exhaust plume may also contribute to infrasound radiation. In either case, the energy available for infrasound excitation is bounded by the rate at which fuel is burned and should be roughly proportional to the total rated thrust of the rocket.

Recent Observations

Recent infrasound observations were collected from waveform data available in the Center for Monitoring Research (CMR) and the IRIS data center. These data serve to provide some insights, source calibration, and ground truth validation. Most of the infrasound data is by necessity very long range (> 1000 km) from large rockets. Observations have been made at infrasound stations, SGAR, DLIAR, and ISM from Space Shuttle Launches at Cape Canaveral and Vandenburg Air Force Station at distances of 100’s to 1000’s of km. Seismic records of infrasound at distances of under 100 km were also collected at broadband seismic stations (Figure 1, Table 1 and Table 2.).

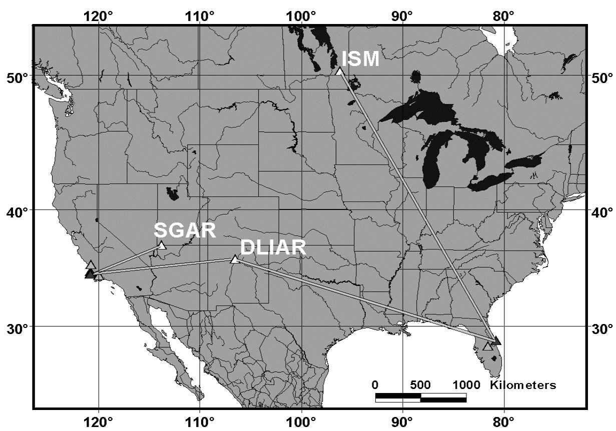

Figure 1. Infrasound arrays DLIAR, SGAR, and ISM detected launches from Cape Canaveral Air Force Station (CCAFS) and Vandenburg Air Force Base (VAFB).

Table 1. 1999 Space Shuttle Launches from Cape Canaveral Air Force Station

	Date GMT	Time GMT	Observed
STS-96	05/27/99	11:49:00	DLIAR
STS-93	07/24/99	04:31:00	DLIAR
STS-103	12/19/99	00:50:00	None

Table 2. 1999 VAFB Launches with rated thrust greater than 200 Klbs.

Date GMT		Rocket	VAFB Location	Thrust Klbs	Detect
1/10/99	08:06	MINUTE-0MAN III	NVAFB	200	No
2/22/99	10:39	DELTA II	SLC2	700	No
3/10/99	08:01	PEACE-KEEPER	NVAFB	500	No
4/15/99	18:32	DELTA II	SLC2	700	DLIAR, SGAR
4/27/99	18:22	ATHENA II	SLC2	400	No
5/22/99	09:36	TITAN IVB	SLC4E	1700	DLIAR, SGAR
6/20/99	02:15	TITAN II	SLC4W	430	No
8/20/99	08:45	MINUTE-MAN III	NVAFB	200	No
8/20/99	11:27	MINUTE-MAN III	NVAFB	200	No
9/24/99	18:22	ATHENA II	SLC6	400	No
10/3/99	02:01	MINUTE-MAN III	NVAFB	200	No
12/12/99	17:38	TITAN II	SLC4W	430	No
12/18/99	18:57	ATLAS IIAS	LC3E/W	700	No

NVAFB=North VAFB, LC2=Launch Complex 2, SLC4E =Space Launch Complex 4 East, SLC4W =Space Launch Complex 4 West, SLC6=Space Launch Complex 6.

Space Shuttle Launches in 1999. It has been observed that “summer season” Space Shuttle launches can be seen at the DLIAR infrasound array in New Mexico (2550 km with nominal travel time of 8500 seconds) and at the more recently installed ISM infrasound array in Canada (2780 km with nominal travel time of 9300 seconds). These low SNR detections (Figure 2) are possible only because signal processing can see coherent signals within the otherwise incoherent background noise. During the favorable summer season, observed peak amplitudes of a few Pa are seen with durations of ~400-500 seconds. It is not possible to determine the actual dominant frequency since the dominant frequency of the recorded signals are at or above the upper end of the of the system bandwidth (~4 Hz). The observations are consistent with the historic long-range Saturn-V signals cited in the literature given the rate of energy release of the Space Shuttle is about the same as a Saturn-V. While we expect propagation effects to extend the duration of the signals, it is not clear to what extent the signal duration is determined by the total burn time of the shuttle engines (~400 seconds) and the fact that the rocket is traveling away from the stations at supersonic speeds. “Winter-season” launches have not been detected at DLIAR or ISM. These seasonal effects are clearly related to the geometry of the winter/summer jet streams. The Whitaker attenuation formula predicts greater than an order of magnitude reduction in the amplitude due to a jet stream core of 50 m/s. Assuming, the already low SNR “summer-season” launch signals are enhanced by a “tail-wind”, the “winter-season” launch signals must be two orders of magnitude below the noise.

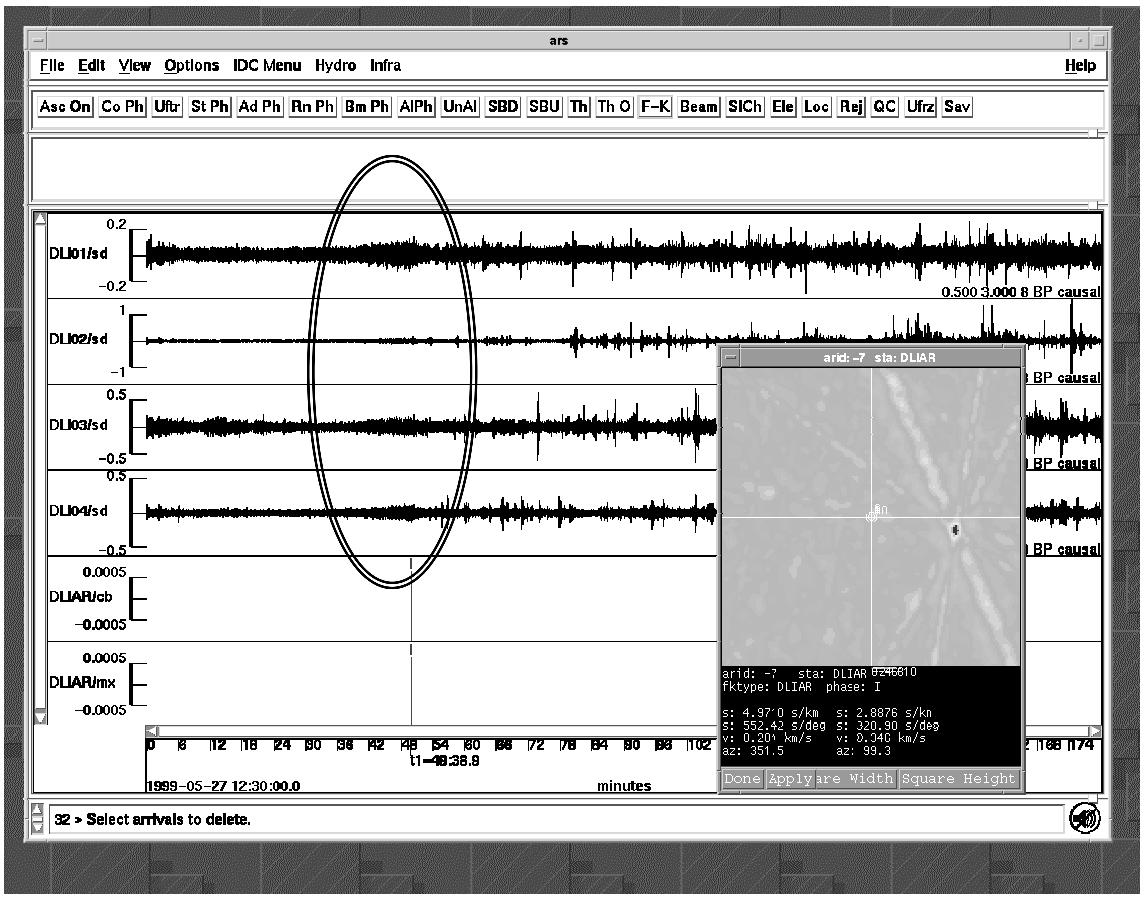

Figure 2. Low SNR arrival recorded at DLIAR in New Mexico from STS-96 launched on 27 May 1999 at 10:49 GMT. The inset frequency wavenumber plot shows a clear stratospheric infrasound arrival (apparent velocity 346 m/s) at the expected back azimuth (99.3 degrees) to CCAFS. Numerous incoherent and unrelated noise bursts can also be seen on the individual traces following the arrival.

A seismometer may serve as a noisy microbarograph. The seismometer responds to pressure waves pushing down on the earth's surface with a conversion efficiency of about one nanometer of vertical ground motion for each microbar of atmospheric pressure variation. Sorrells and Der (1970) give the relation, $v = u2\pi f = c\, P(\lambda + 2\,\mu)/2\mu/(\lambda+\mu)$, where v is the ground velocity, u the ground displacement, c is the infrasound phase velocity, P is the infrasound pressure, and λ and μ are the Lame and shear modulii. Seismic data was available from the IRIS data center for the seismic station DWPF (installed in June 1999) for one shuttle launch (Figure 3). The instrument response is flat to ground velocity (and hence infrasound pressure) across the bandwidth of interest. Figure 4 shows a recording of STS-93 (07/24/99 04:31:00GMT) at DWPF (97 km). The largest seismic amplitudes are consistent with peak infrasound pressures of about 200 microbars. A small signal consistent with a seismic P-wave arrival (P at LO+15s) and S-wave arrival (S at LO+25s) can be seen soon after lift off (LO). The first infrasound arrival (I1 at LO+300s) is consistent with direct tropospheric propagation of the lift off transient at ~320-330 m/s with a sustained amplitude of ~50 nm/s. The larger infrasound signals I2 and I3 probably originate later, higher, and farther down range with peak amplitudes of ~200 nm. The seismic P & S waves as well as the infrasound signals I1 and I2 are peaked near 4 Hz. The infrasound signal I3 is more broadband. No signal is observable below 1 Hz due to high ground noise levels at low frequencies. The total infrasound signal lasts ~400 seconds. The dominant frequency (~4 Hz) at DWPF is consistent with the long-range infrasound signals observed at DLIAR.

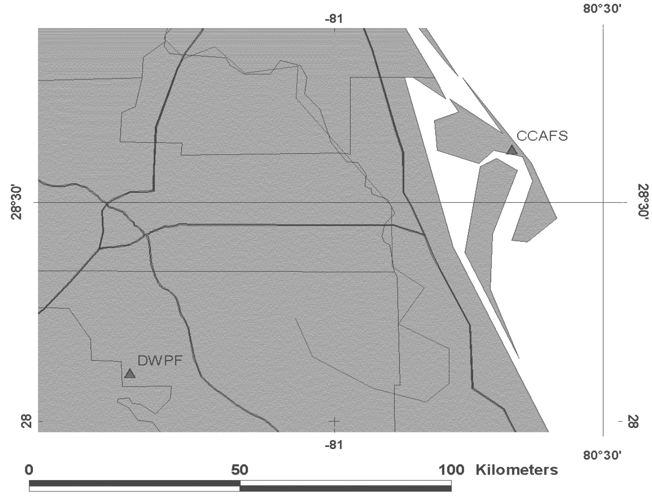

Figure 3. Seismic station, DWPF, is 97 km from the Shuttle Launch pads at Cape Canaveral Air Force Station CCAFS.

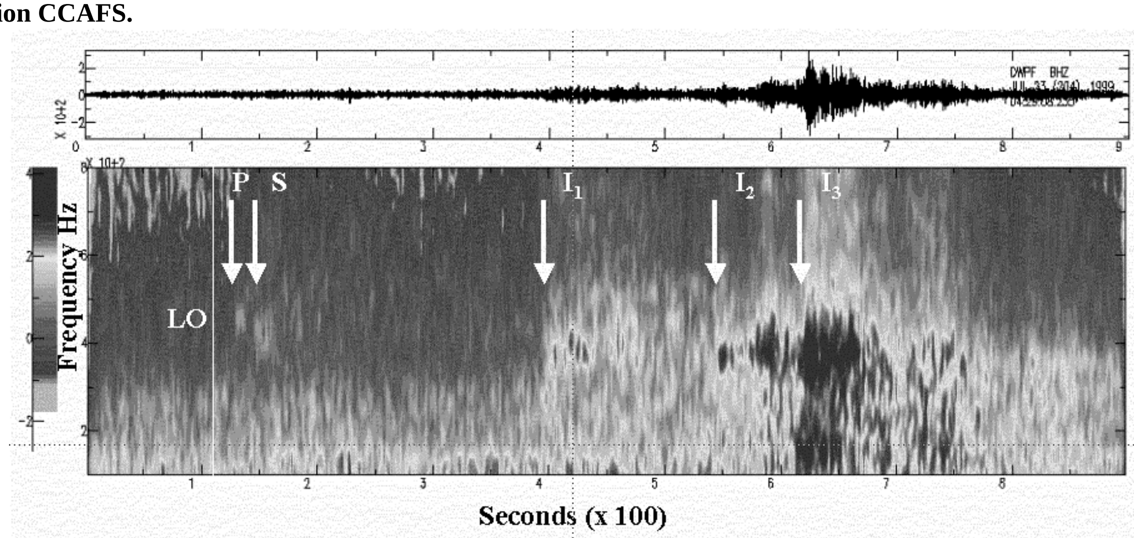

Figure 4. STS-93 (07/24/99 04:31:00GMT) at seismic station DWPF in central Florida (97 km from the launch pad). Sonogram below the seismogram shows frequency content as a function of time. A small signal consistent with a seismic P-wave arrival (P) and S-wave arrival (S) can be seen soon after lift off (LO). The first infrasound arrival (I1) is consistent with direct tropospheric propagation at 330 m/s.

VAFB Launches in 1999. In order to take advantage of favorable West-to-East propagation, waveform data was examined for signals from Vandenburg AFB launches during 1999 (Table 2). Data from eight of 14 launches were examined at SGAR (680 km) and DLIAR (1300 km). Detections were only seen for the Titan IVB of 5/22/99 (see Figures 5A & 5B) and the Delta II of 04/15/99. Interestingly, the Delta II of 02/22/99 and the Atlas IIA of 12/18/99 were not detected although these two rockets are of similar size. No rockets rated less than 700 Klbs thrust were detected. Relative amplitudes of the Delta II and Titan IVB are consistent with the relative thrusts (700 vs. 1700 Klbs). All observed azimuths of arrival were within 5 degrees of nominal (250 and 269 degrees at SGAR and DLIAR respectively). Arrival times and phase velocities are consistent with stratospheric propagation and nominal infrasound travel times to SGAR and DLIAR of 2340 and 4440 seconds respectively. The signals were best observed between 0.1 and 2 Hz. The Infratool analysis in Figure 6 demonstrates the back-azimuths are consistent and within 5 degrees of the launch site although there is evidence that the back-azimuth does decrease with time consistent with the trajectory of the rocket to the southwest of the launch site.

Seismic data was examined from two Caltech seismic stations PHL (65 - 85 km from VAFB launch facilities) and SBC (84 - 91 km from VAFB launch facilities) available from the IRIS data center. Four launches recorded at PHL are shown in Figure 7. The dominant frequencies of all signals are at the upper end of the bandwidth (7-8 Hz) and well above the long-range infrasound bandwidth observed at SGAR and DLIAR (0.1-2 Hz). Peak amplitudes vary from ~300 to 600 microbars, however, the amplitudes do not correlate well with range or thrust. A couple of the infrasound signals appear to arrive early (assuming 340 m/s propagation) suggesting that the launches were not exactly on the minute. Data dropouts produce spikes on two recordings and should not be confused with real arrivals. The set of five launches show extreme variability in onset and duration. The rockets were traveling away from the station and the signal durations are very extended lasting 400-500 seconds. Three of the signals show large transients near the end (a Delta II and two Minuteman III's). The two bottom traces in Figure 7 are Minuteman III's launched from the same area (NVAFB) separated by only 2 hours 42 minutes. These two records demonstrate the strong dependence of infrasound on meteorological conditions. While there are some similarities between the two records and the launch times may be uncertain, the timing between the arrivals is not reproduced. The spectral character of the signals at this range is quite different from the long-range signals recorded at SGAR and DLIAR. Sonograms of these records (Figure 8) show arrivals are characterized by 2-8 Hz broadband impulses and 4-8 Hz continuous coda.

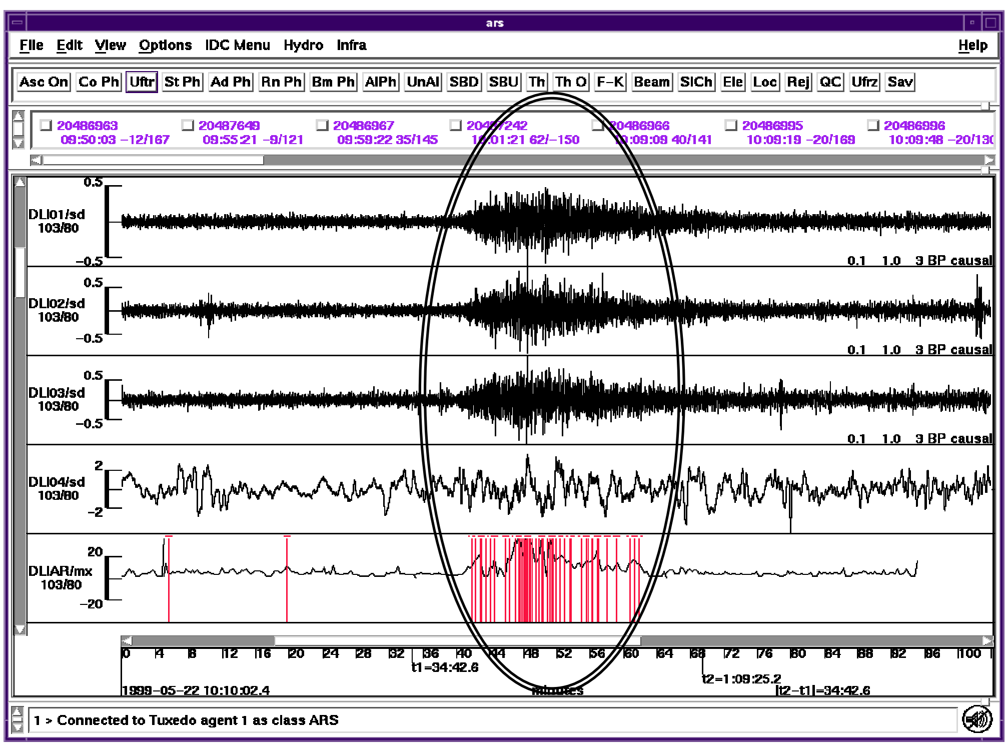

Figure 5A. Titan IVB 05/22/99 recording at DLIAR (1300 km).

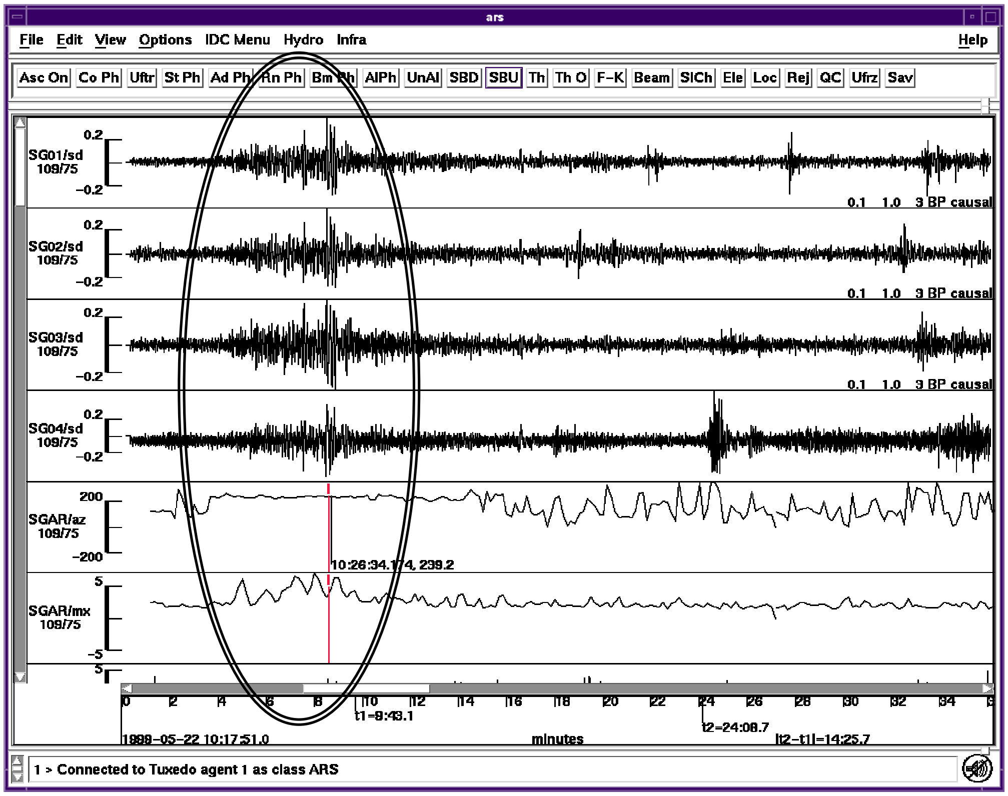

Figure 5B. Titan IVB 05/22/99 recording at SGAR (680 km).

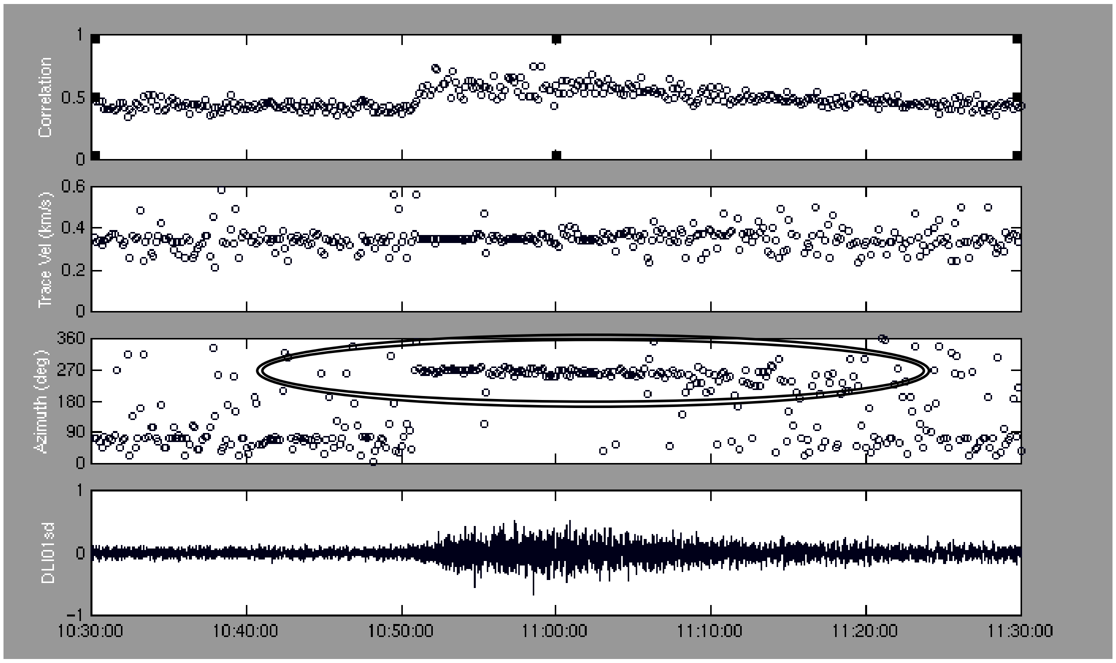

Figure 6. Infratool (SANDIA, DoE 1999) analysis of the Titan IVB recording at DLIAR (1300 km) shows azimuth of arriving energy is initially constant and within 5 degrees of nominal for ~5 minutes and then slowly decreases consistent with the rocket's trajectory to the southwest of VAFB.

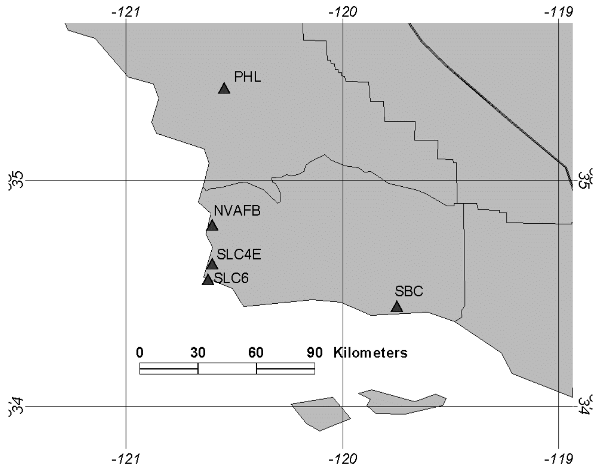

Figure 7A. Caltech station PHL is available from IRIS and between 65 and 85 km of launch facilities at VAFB. Signals were also observed at SBC.

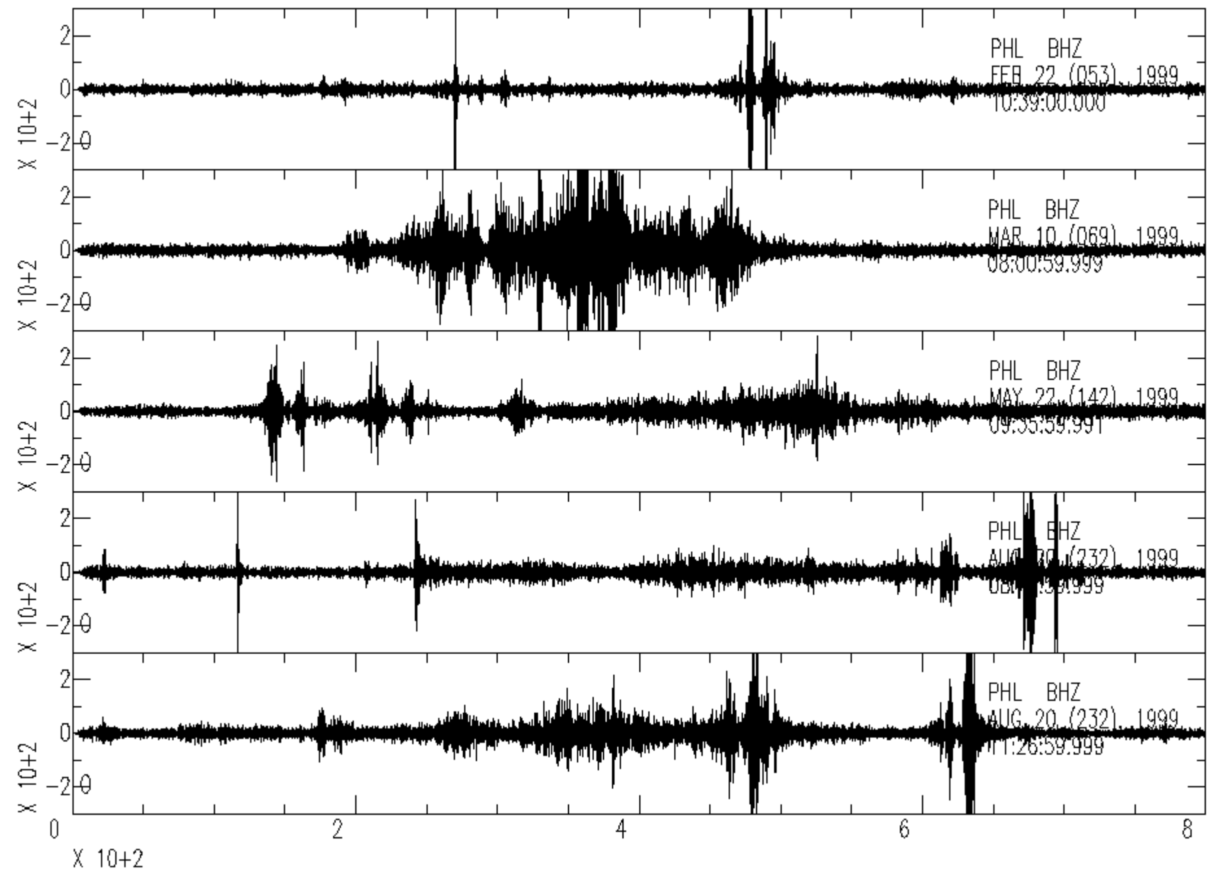

Figure 7B. Seismic recordings of five launches from VAFB at station PHL (1-8 Hz). All traces are aligned on announced lift off times (given to the minute) and plotted on the same time and amplitude scales. Ranges to the launch facilities vary from 65 to 85 km. A couple of the infrasound signals appear to arrive early suggesting launches were not exactly on the minute. Data dropouts produce spikes on two recordings. The set of five launches show extreme variability in onset, amplitude, and duration. Three of the signals show large transients near the end of the record. The two bottom traces are Minuteman III's launched from NVAFB separated by only 2 hours 42 minutes.

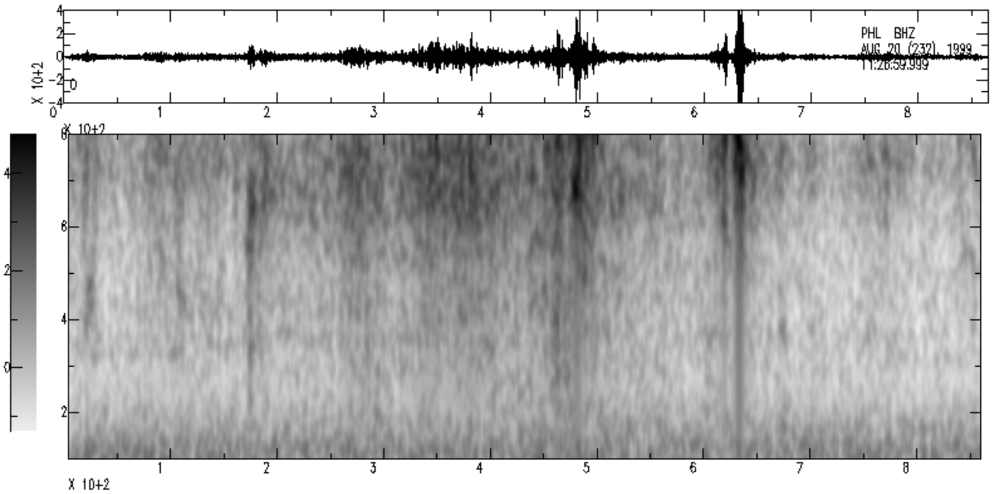

Figure 8. Spectrogram of 11:27 Mar 20, 1999 MINUTEMAN III launch from NVAFB at seismic station PHL (~68 km). Acoustic arrivals are characterized by broadband (2-8 Hz) impulses superimposed upon more continuous 4-8 Hz coda.

Propagation

Both climatological and daily meteorological models are available to compare with infrasound observations. Figure 9 contrasts the 200 mb wind (~10 km) velocities for May 27, 1999 (Space Shuttle detection at DLIAR) and December 19, 1999 (no Space Shuttle detection at DLIAR). The high altitude winds (10 Km) differ by over a factor of two between these two dates. Figure 10 shows predicted ray paths for two simpler climatological models. The presence of a strong west to east mid-latitude jet stream inhibits propagation from east to west during the winter. During "summer" periods when the jet stream is weak or absent across the United States, a stratospheric waveguide may support east to west propagation. Obviously, more detailed 3D analysis of specific days for which long-range detections (and non-detections) are observed should be used to test numerical infrasound propagation predictions.

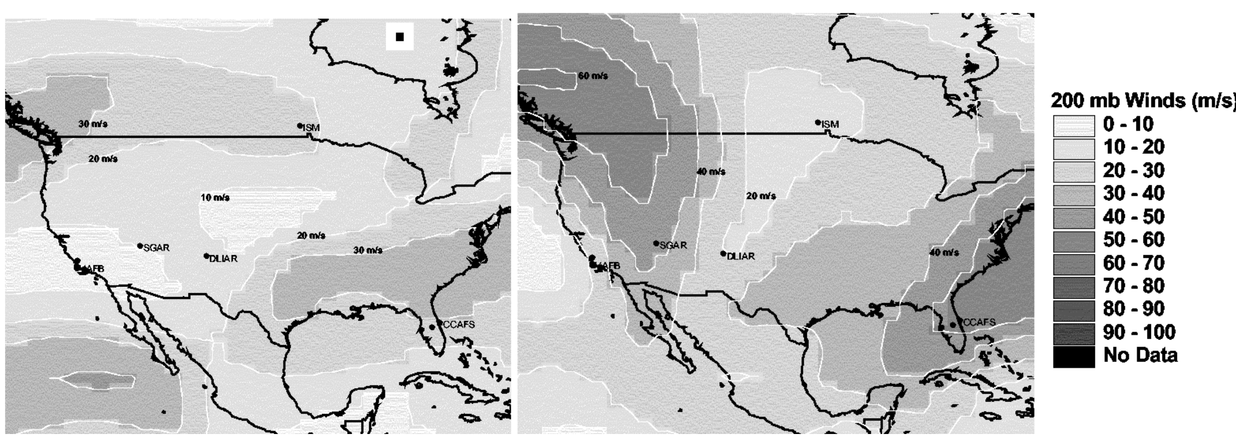

Figure 9. Contours for winds at 200 mb for May 27, 1999 (LEFT) and December 19, 1999 (RIGHT). Stratospheric winds between CCAFS and DLIAR or between CCAFS and IMS for the May 27 Space Shuttle launch (positive detection) were light in contrast to December 19 (no detection).

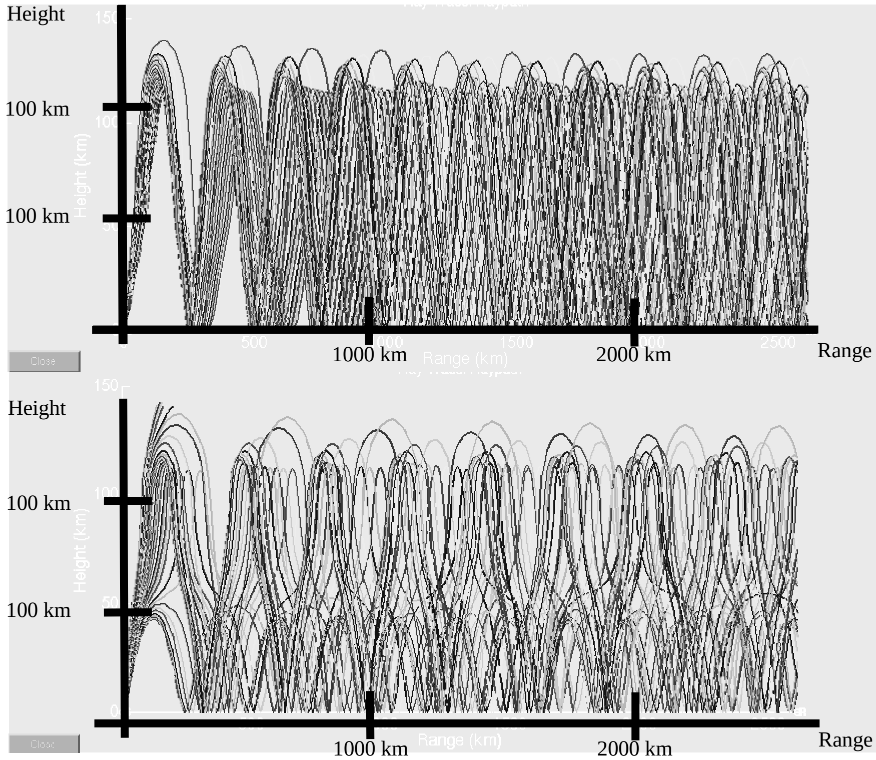

Figure 10. Ray paths predicted by "Inframap" (Norris et al. 1999 and Gibson et al. 1999) for the path from CCAFS to DLIAR for January (TOP) and July (BOTTOM) climatological models. Only a thermosphere return exists in the "winter" due to a dominant east to west mid latitude jet stream. During the "summer", a stratospheric return is present.

CONCLUSIONS AND RECOMMENDATIONS

The satellite launch industry is a multibillion-dollar international industry with over 100 commercial and military satellite launches conducted in 1999 alone. These diverse rocket launches may serve as useful future "ground truth" data to test and calibrate IMS infrasound system capabilities. Potential commercial and military launch facilities include Baykonyr in Kazakhstan, Plesetsk in Russia, Jinyu, Wuzhsi, Jiuquan, Xichang, and Taiyuan in China, Woomera in Australia, Kourou in French Guinea, Tenegashima in Japan, Vandenburg AFB, Cape Canaveral AFS, and the new Boeing ocean-going Sea Launch platform (Figure 11.). While IMS class arrays are not necessarily optimal for detecting rocket launches, observations demonstrate very low-yield atmospheric detection thresholds (~0.1-1 tons) at over 1000 km under favorable atmospheric conditions. Routine observations of announced launches also provide opportunities to further study dependence of long-range infrasound amplitudes with respect to stratospheric winds. As the IMS infrasound network becomes denser, it should be possible to test and validate 3D propagation codes.

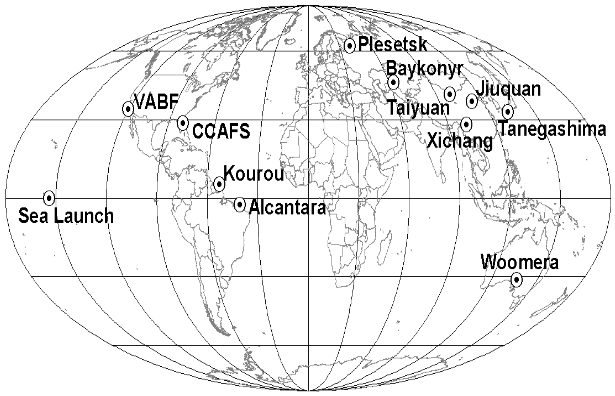

Figure 11. The future IMS infrasound system should observe orbital rocket launches from a dozen potential commercial sites worldwide.

Observations in this report of short-range infrasound (< 100km) recorded on seismic systems compared to long-range recordings on microbarograph systems indicate that the short-range frequency content may be much different than long-range frequency content. This may be due to propagation effects or it may be due to different effective source (excitation) mechanisms and propagation. Researchers in the 1960's concluded that long-range infrasound was generated by the supersonic shock waves. At closer distances, engine exhaust may also be a significant source of infrasound.

A comprehensive search of rocket-generated long-range infrasound on systems archived at the PIDC should be made so that automatic detectors could be tuned for these valuable signals. Amplitudes and azimuths of arrival should be compared to nominal values for each launch site and launch vehicle. Noise levels for non-detections of announced launches should be routinely measured and documented. These observations should then be compared with theoretical predictions based on climatological and specific daily meteorological models.

Acknowledgements

We wish to thank Rod Whitaker of LANL and Bob Blandford of AFTAC for helpful comments.

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Keith McLaughlin (scatter@cmr.gov), Anna Gault (gault@cmr.gov), David Brown (djb@cmr.gov).

Key Words: Infrasound, rocket launches